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AN INTEGRATED MODEL OF DRILLING VESSEL OPERATIONS

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A combined discrete-event/continuous/process-interaction simulation model has been developed to evaluate the effects of weather and supply-ship availability on offshore drilling operations at a specified location and time of year with a specified drilling vessel. The continuous submodel includes: (a) autoregressive-moving average and transfer-function models to represent weather conditions; (b) a difference equation to monitor effective work time for the current operation on the drilling vessel; (c) difference equations to govern supply levels on all vessels; (d) state-events to stop and restart operations on all vessels; and (e) difference equations to control the movement of supply ships. The process-interaction submodel represents the flow of supply-ship traffic and the overall operation of the drilling vessel. The discrete-event submodel controls the loading and unloading of supply ships as well as the alternation of periods of calm and stormy weather.

1. INTRODUCTION

Exploration activity of major oil companies has become strongly oriented toward offshore projects. Wells are being drilled in deeper waters hundreds of miles from supply ports. The commitment to projects in the Arctic seas has resulted in weather-related problems not encountered in land operations or offshore projects conducted in milder climates. There is a wide range in both performance and cost of floating drilling vessels contracted for these projects. For example, semisubmersibles are more stable in rough seas than drill ships; however, semisubmersibles can carry fewer supplies and in general have a higher daily contracting cost. The rate at which a given activity can be performed is typically a function of either the wave height or the heave of the drilling vessel. Although less stable vessels require more time to complete a project, such vessels generally have a lower rental cost per day.

Weather conditions also affect the following operations: (a) movement of supply ships between the supply port and the drilling site; and (b) the offloading of supplies to the drilling vessel. In addition, supply boats vary significantly in their operating characteristics and contracting cost. It is important to select the most suitable drilling vessel and supply-boat fleet in order to avoid excessive interruption of activities due to either insufficient supplies or adverse weather conditions. Such downtime will delay the completion of the project. This is a particularly critical problem when a well is being drilled in order to obtain data prior to a lease sale, or when the project is being carried out during the fall season and the site must be abandoned before the onset of the winter ice.

A general simulation model that integrates submodels of the associated weather processes, drilling vessel operations, and supply-related activities was developed at The University of Texas for the Atlantic Richfield Oil and Gas Company. This simulation system is currently being used to: (a) evaluate alternative drilling vessels for projects in specific regions using typical weather conditions for a given time of year; and (b) determine the effect of different well designs on the completion time of the project.

1.1 Problem Statement

ARCO previously developed a model coded in FORTRAN to predict the performance of floating drilling vessels. Weather conditions were represented as a simple Markov chain whose states were defined as a combination of wave height and wave period. The response variable, heave, was defined as a function of the wave spectral density and the response amplitude operator for the drilling vessel. This model did not include any supply activities as they are not typically critical when the well location is near the supply port or when weather conditions are not adverse.

The company requested the development of a more extensive model that could be used to predict downtime for wells to be drilled in the Bering Sea during the period 1982-1983. In particular, ARCO required a refined weather model based on Box-Jenkins time series methodology. Because one of the wells is 600 miles from the supply port, a detailed model of supply ship operations was also required for optimal sizing of the fleet of supply ships. In addition, it was stipulated that (a) the nominal effective work time for each activity on the drilling vessel should incorporate random variation; and (b) the associated activity completion rates should depend dynamically on wave height and wave period as well as on the level of all required supplies. Finally, ARCO requested that a formal simulation language be used in the development of the model.

1.2 Modeling Objectives

The first major objective was to apply Box-Jenkins time series analysis techniques to build a generally applicable class of univariate models of the weather processes (Box and Jenkins 1976). Calm models were initially constructed for wave period, wave height, and wind speed; and then different classes of storms were superimposed via step functions using intervention analysis (Box and Tiao 1975). Transfer function analysis techniques were employed to model the calm-weather wave height process with wind speed as an input. Different classes of storms were similarly introduced into the transfer function model as intervention variables.

The second major objective was to integrate all of the previously described aspects of drilling-vessel operations into a SLAM simulation model (Pritsker and Pegden 1979). This model was designed to evaluate the effect of each of the following factors on the percentage of downtime for a given well design: (a) type of drilling vessel, (b) weather conditions, (c) supply-ship fleet size, and (d) rig-to-port distance.

2. MODEL DEVELOPMENT

2.1 System Description

Overall system flow Drilling vessel operations are performed sequentially as designated by a given well design. The duration of each operation during calm weather is well known from past experience, although it can vary according to crew capabilities. A typical well schedule for an exploratory well is shown in Figure 1, where mean activity times are specified for fair weather operation. Efficiency of operations is a function of either the wave height or the heave of the drilling vessel. If the weather is severe enough, operations are actually halted, the riser is disconnected, and delays occur. Typical operating efficiencies for a semisubmersible are shown in Table 1.

The cycle of operations for a supply ship begins when the ship fills up with supplies at the port. Drilling operations start when the supply ship arrives at the well site. As soon as the drilling vessel is anchored, the first supply ship can begin unloading. Different supplies are unloaded consecutively in order of need. This activity terminates when either (a) the rig cannot accomodate any more supplies; or (b) a supply becomes critical on the drilling vessel, and the supply ship is also out of that commodity. If in case (b) there is another supply ship on site, the original supply ship then returns to the port with any remaining supplies. (There must always be at least one supply ship on the site for safety reasons.) Rig-to-port travel time depends on the roughness of the seas. Upon arrival at the port, the supply ship is reloaded with supplies. Weather permitting, the supply ship immediately returns to the site where it waits to be unloaded.

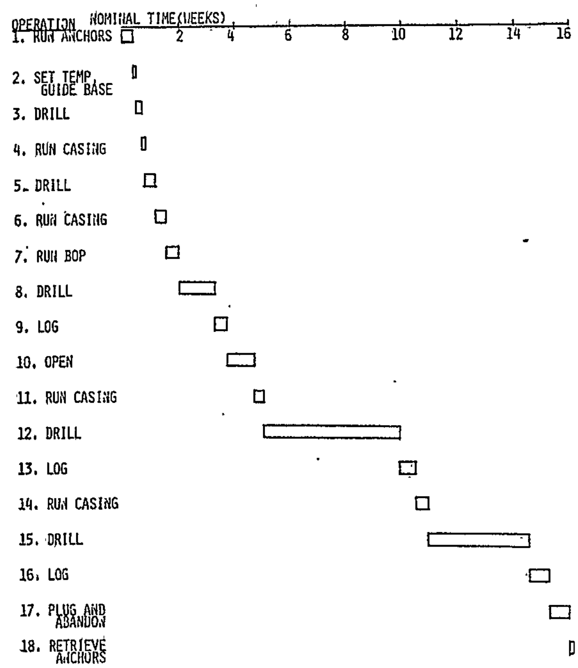

Figure 1: Fair-Weather Exploratory Well Schedule

The following supplies are required for operation of the drilling vessel: fuel, drilling mud components (water, barite, and gel), cement, and steel casing (deck cargo). Fuel is consumed throughout the entire operation at a nearly constant rate, although less is used when operations go down. Drilling mud supplies are required after the anchoring is completed. Water and gel are consumed at a constant rate throughout the remaining operations, while the barite usage rate increases as the drilling progresses. Usage of cement and deck cargo is activity dependent, as these supplies are only required when the steel casing is run. Hence, cement and deck cargo are brought from the port just before they are needed. In practice, drilling operations are completed when the last activity is finished. At ARCO's directive, the well is considered to be complete only when there are enough supplies on board the drilling vessel to begin drilling another well.

System constraints The drilling vessel operates within certain constraints pertaining to the unloading of supplies. When an operating limit is reached for a supply level on the drilling vessel, a predetermined action must be taken. If a supply is being unloaded and its respective storage capacity is reached, unloading of that supply is stopped, and another supply is unloaded. The supply that reached capacity may be unloaded later when its level has been sufficiently reduced. In addition, there are specified minimum supply levels required

Table 1: Operating Efficiencies for a Semisubmersible

OPERATION	OPERATING EFFICIENCY	OPERATING RANGE	RECONNECT TIME (DAYS)
1. Run anchors	100% 75% 0%	0.0-5.0 ft wave ht 5.0-7.5 ft wave ht >7.5 ft wave ht	---
2. Drill 36" hole to 700'	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-20.0 ft heave >20.0 ft heave <5.0 ft heave	0.5
3. Set 30" casing at 700'	100% 75% 0% DISCONNECT RECONNECT	0.0-4.0 ft heave 4.0-8.0 ft heave 8.0-20.0 ft heave >20.0 ft heave <5.0 ft heave	1.0
4. Drill 26" hole to 1000'	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-20.0 ft heave >20.0 ft heave <5.0 ft heave	0.5
5. Run 20" casing and set BOP	100% 75% 0% DISCONNECT RECONNECT	0.0-3.0 ft heave 3.0-5.0 ft heave 5.0-20.0 ft heave >20.0 ft heave <3.0 ft heave	1.5
6. Drill 12.25" hole	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <5.0 ft heave	0.5
7. Log	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <5.0 ft heave	1.0
8. Open hole to 17.5" to 2000'	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <5.0 ft heave	0.5
9. Set 13.375" casing at 2000'	100% 75% 0% DISCONNECT RECONNECT	0.0-4.0 ft heave 4.0-8.0 ft heave 8.0-14.0 ft heave >14.0 ft heave <4.0 ft heave	1.5
10. Drill 12.25" hole to 5000'	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <4.0 ft heave	0.5
11. Log	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <4.0 ft heave	1.0
12. Set 9.625" casing at 5000'	100% 75% 0% DISCONNECT RECONNECT	0.0-4.0 ft heave 4.0-8.0 ft heave 8.0-14.0 ft heave >14.0 ft heave <4.0 ft heave	1.5
13. Drill 8.5" hole to 7000'	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <5.0 ft heave	0.5
14. Log	100% 75% 0% DISCONNECT RECONNECT	0.0-8.0 ft heave 8.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <5.0 ft heave	1.0
15. Set 7" liner at 7000'	100% 75% 0% DISCONNECT RECONNECT	0.0-4.0 ft heave 4.0-8.0 ft heave 8.0-14.0 ft heave >14.0 ft heave <4.0 ft heave	1.5
16. Test	100% 75% 0% DISCONNECT RECONNECT	0.0-4.0 ft heave 4.0-8.0 ft heave 8.0-14.0 ft heave >14.0 ft heave <4.0 ft heave	1.5
17. Plug and abandon	100% 75% 0% DISCONNECT RECONNECT	0.0-6.0 ft heave 6.0-10.0 ft heave 10.0-14.0 ft heave >14.0 ft heave <5.0 ft heave	0.5
18. Retrieve anchors	100% 75% 0%	0.0-5.0 ft wave ht 5.0-7.5 ft wave ht >7.5 ft wave ht	---

for sustaining operations. If a supply is nearly critical, it is beneficial to cease unloading the current supply and begin unloading the one that is needed. This is possible, of course, if the nearly critical supply is on board the supply ship that is currently unloading. If this supply cannot be unloaded and its critical level is reached, operations are halted. The next supply ship then begins unloading the critical supply while the first supply ship returns to port. When the critical supply rises to a specified minimum level, operations may begin again. Another problem can potentially occur with respect to cement and deck cargo. As noted, these supplies are scheduled to arrive just prior to their use. Operations are halted if these supplies do not arrive early enough due to severe weather conditions encountered between the port and the drilling site. Finally, there is a total weight capacity constraint for all supplies on the drilling vessel. If this level is reached, no supplies can be unloaded until the total weight is sufficiently reduced.

2.2 Weather Model

Modeling methodology The efficiency of operations on the drilling vessel is determined by either the height of the waves or the heave of the drilling vessel, which is itself a function of both the wave height and wave period. The speed of travel of supply boats and their ability to offload supplies is also related to wave height. Thus it was necessary to develop valid empirical models of these weather related variables in order to generate process data for the simulation.

Box-Jenkins time series methodology (Box and Jenkins 1976) was employed to model wave height and wave period. In general, the functional form of such univariate models is ascertained by examination of the sample autocorrelation and partial autocorrelation functions. Least squares estimates of the coefficients are computed, and diagnostic checking of the models is performed. The resulting ARMA models are of the form

$$\phi(B)(z_t - \mu) = \theta(B)a_t \qquad (1)$$

where

z_t = Discrete process measured at equal time intervals 1, 2, ..., t-1, t, t+1, ...;

μ = Mean level of the process;

$\phi(B) = 1 - \phi_1 B - \dots - \phi_p B^p$ = Nonseasonal autoregressive (AR) operator, a polynomial of order p in the backward shift operator B;

$\theta(B) = 1 - \theta_1 B - \dots - \theta_q B^q$ = Nonseasonal moving average (MA) operator, a polynomial of order q in the backward shift operator B; and

a_t = Independent normally distributed white noise residual with mean 0 and variance σ_a^2.

Initially models are developed for calm periods at a specific site during a particular season. Thus the processes are stationary in their means, so no differencing is required. The interseasonal characteristics of wave data can vary markedly. Unfortunately, time series for remote drilling sites are not usually long enough to develop seasonal models, so the data analysis is restricted to development of models for specified lengths of time with homogeneous seasonal characteristics.

Storm periods are modeled as step functions in an intervention model (Box and Tiao 1975), where such periods are designated according to wave height as members of one of three classes of storms. These intervention models have the functional form

$$z_t - \mu = \sum_{i=1}^{3} w_i I_{it} + \frac{\theta(B)}{\phi(B)} a_t, \quad (2)$$

where

- w_i = Coefficient of the intervention variable associated with the i^{th} storm class, and
- I_{it} = Binary indicator variable denoting the occurrence of a storm of class i at time t.

All remaining variables and parameters in (2) are defined as in (1). It is assumed that the noise component of the intervention model has the same functional form as the calm period models.

Typically changes in wind speed precede the corresponding movements in levels of wave height and wave period. Calm weather transfer function models are developed which reflect this relationship such that in general

$$z_t - \mu = \frac{\omega(B)}{\delta(B)} X_{t-b} + \frac{\theta'(B)}{\phi'(B)} a_t', \quad (3)$$

where

- z_t = Discrete time series denoting the output variable;
- μ = Mean level of the output variable;
- X_{t-b} = Discrete time series denoting the input variable, where b is the lag or number of intervals by which the input variable series precedes the output variable series;
- $\omega(B) = \omega_0 - \omega_1 B - \ldots - \omega_s B^s$ = Right-hand polynomial operator of order s in the transfer function relationship $\delta(B)z_t = \omega(B)X_{t-b}$ between z_t and X_{t-b};
- $\delta(B) = 1 - \delta_1 B - \ldots - \delta_r B^r$ = Left-hand polynomial of order r in the transfer function relationship between z_t and X_{t-b};
- $\theta'(B)$ = Nonseasonal moving average operator in the noise component of the transfer function model;
- $\phi'(B)$ = Nonseasonal autoregressive operator in the noise component of the transfer function model; and
- a_t' = Independent normally distributed white noise residual with mean 0 and variance $\sigma_{a'}^2$.

The functional form of the transfer function model is identified from the sample cross correlation function between the prewhitened calm weather input variable and the filtered output variable. Thus it is necessary to develop a univariate calm period model and then an intervention model with step functions to represent levels of wind speed throughout the period of interest. The functional form of these models is shown in (1) and (2). Estimates of the respective intervention components for both the input and output series are removed from these series in order to yield a longer sample record for the identification of the calm weather transfer function relationship.

A transfer function model containing intervention variables to indicate the occurrence of step changes in the level of the dependent variable due to storms is then developed to fit the entire series of data as follows:

$$z_t - \mu = \sum_{i=1}^{3} w_i' I_{it} + \frac{\omega(B)}{\delta(B)} X_{t-b} + \frac{\theta'(B)}{\phi'(B)} a_t', \quad (4)$$

where

- X_{t-b} = Fair weather wind speed at time t-b;
- w_i' = Increment in the level of the output variable due to a storm of class i; and

all other variables and parameters are defined as in (3). It is assumed that (a) the same transfer function relationship is valid for both calm and storm periods; and (b) all changes in the level of the output variable during storm periods are adequately modeled by the intervention variables in (4).

<u>Empirical weather model</u> To develop a typical weather model, ARCO provided twelve-hour hindcast data for wave period, wave height, and wind speed in the Gulf of Alaska. These data are a composite of observations from satellite maps, recorded weather station data, and ships' reports for a specific area during a given time period. Such data sets are typically selected from "worst case" years for planning expensive projects that potentially involve a high degree of weather-related risk. In this study the sample records were specifically selected to represent an Arctic environment with storms of all three classes. In addition to providing an opportunity to test the ability of the model to track both calm and severe weather, these storm periods increased the likelihood of encountering downtime on the drilling rig. The fall season data were analyzed because the highest waves occur during this time of year.

The fitted univariate calm period models of wave height, wave period, and wind speed are summarized in Table 2. All of the estimated coefficients have significance probabilities less than 5%, and the residuals pass the usual white noise tests.

The three storm classes were defined for wave height and wave period according to Table 3 using the maximum value of each variable attained during the storm. The coefficients of the intervention models

Table 2: Parameter Estimates for Calm Weather ARMA Models

Process	Model Form	Parameter Estimates
Wave Period	AR(1)	μ = 6.6 sec^{-1}
		ϕ_1= 0.58
Wave Height	AR(1)	μ = 5.5 ft
		ϕ_1= 0.49
Wind Speed	ARMA(1,1)	μ = 8.8 knots
		ϕ_1= 0.28
		θ_1=-0.12

Table 3: Storm Class Designations

Maximum Wind Speed (knots)	Maximum Wave Height (ft) (10, 15]	(15, 20]	(20, ∞)
(22, 35]	1	2	3
(35, 48]	2	2	3
(48, ∞)	3	3	3

for wave height were fit assuming the same functional form of the noise model as was identified for calm periods. The estimated coefficients have significance probabilities less than 5%, and the sample autocorrelation functions of the residuals do not have identifiable patterns at low order lags that could be used to modify the model. The chi-square value calculated for the portmanteau lack-of-fit test was inflated (particularly for the wave period model) due to significant high order autocorrelations in the estimated residuals. The estimates of the coefficients are shown in Table 4. Because the storms were classified according to peak values achieved during each incident, but the estimates of the step function correction terms or intervention coefficients were calculated using actual values realized during the storm, the numerical values are smaller than the threshold values used in the storm classification.

Transfer function models of both wave height and wave period were considered with wind speed as the input variable. The cross correlation function between the prewhitened wind speed variable and wave period had no significant values at low order lags. This was surprising, as short period waves are known to be related to wind speed. ARCO conjectured that this result could possibly have been attributed either to the influence of swell which is not related to local wind conditions, or to the quality of the hindcast wave period data. It is expected that a relationship would be indicated between wind speed and wave period if actual measurements were collected from a buoy at shorter time intervals.

The cross correlation function between the fair

Table 4: Parameter Estimates for Univariate Intervention Models

Process	Operator Type	Parameter Estimates
Wave Period		μ = 6.7 sec^{-1}
	AR(1)	ϕ_1= 0.47
	Intervention 1	w_1= 0.2 sec^{-1}
	Intervention 2	w_2= 1.5 sec^{-1}
	Intervention 3	w_3= 2.1 sec^{-1}
Wave Height		μ = 6.8 ft
	AR(1)	ϕ_1= 0.44
	Intervention 1	w_1= 4.3 ft
	Intervention 2	w_2= 7.2 ft
	Intervention 3	w_3= 8.3 ft
Wind Speed		μ = 10.9 knots
	ARMA(1,1)	ϕ_1= 0.19
		θ_1= -0.28
	Intervention 1	w_1= 8.0 knots
	Intervention 2	w_2= 12.3 knots
	Intervention 3	w_3= 16.5 knots

weather wind speed and wave height indicated that the relationship between the input and output variables contained both input and output lag operators. Estimates of the parameters for the calm weather model are shown in Table 5. The contemporaneous relationship between the variables implied by the zero-valued lag b is a result of the twelve-hour time increment between observations. For shorter intervals, this value is usually strictly positive.

Table 5: Parameter Estimates for Calm Weather Transfer Function Model

Process	Operator Type	Parameter Estimates
Wave Height		μ = 5.1 ft
	Input Lag $\omega(B)$	ω_0= 0.15
		ω_1= 0.12
	Output Lag $\delta(B)$	δ_1= 0.64
		δ_2= 0.35
	Autoregressive $\phi'(B)$	ϕ'_1= 0.58
	Lag b	b = 0

The intervention terms for the transfer function model were developed using step functions in wave height. The estimates of the parameters in the final model are shown in Table 6. This model fit the data extremely well, as indicated by the lack of autocorrelation among the residuals and the lack of cross correlation between the residuals and the input variable. The parameter estimates in the output lag polynomial, $\delta(B)$, differed from those of the

Table 6: Parameter Estimates for Transfer Function Intervention Model

Process	Operator Type	Parameter Estimates
Wave Height		$\mu = 7.3$ ft
	Input Lag $\omega(B)$	$\omega_0 = 0.16$
		$\omega_1 = 0.14$
	Output Lag $\delta(B)$	$\delta_1 = 1.14$
		$\delta_2 = -0.19$
	Autoregressive $\phi'(B)$	$\phi_1' = 0.42$
	Intervention 1	$w_1' = 3.6$ ft
	Intervention 2	$w_2' = 6.1$ ft
	Intervention 3	$w_3' = 7.0$ ft
	Lag b	$b = 0$

calm weather model by more than expected. All other values were consistent with the estimates in Table 5.

The wave period values for the simulation were generated using the intervention model indicated in Table 4. Calm weather wind speed values were generated from the AR(1) model in Table 2 and employed in the transfer function relationship with the estimates of the input and output lag coefficients of Table 6. Changes in level due to storm periods were computed using the estimates of the intervention coefficients in Table 6. Using three years of data recorded at two sites in the Gulf of Alaska, we constructed empirical distributions by month for the class, duration, and interoccurrence time of individual storms. These distributions were employed to generate the storm process required for the time series intervention models.

3. MODEL DESCRIPTION

The integrated model of drilling vessel operations consists of three submodels based respectively on the capabilities of SLAM for continuous, process-interaction, and discrete-event simulation. The conceptual organization of each submodel is detailed below. Because of the intricate interconnections among the submodels, this trichotomy can be viewed in several different ways. Nevertheless, clear-cut advantages are realized by using a combined simulation model in this study.

3.1 Continuous Submodel

All of the system status variables defined by difference equations (the so-called state variables) belong to the continuous submodel. This scheme includes the time series models that are updated every 12 hours: (a) the intervention model taken from Table 4 for the wind speed V; (b) the intervention model taken from Table 4 for the wave period T; and (c) the transfer-function/intervention model taken from Table 6 for the wave height H with the wind speed input generated according to Table 2. In terms of the corresponding wave spectral density

$$S(\xi) = 4200H^2T^{-4}\xi^{-5}\cdot\exp(-1050T^{-4}\xi^{-4}), \quad (5)$$

and the response amplitude operator of the drilling vessel

$$\text{RAO}(\xi) = \text{Heave [ft] / Wave height [ft] for waves with circular frequency } \xi, \quad (6)$$

the (significant) heave of the drilling vessel is

$$Z = [\int_0^\infty S(\xi)\cdot\text{RAO}^2(\xi)d\xi]^{1/2} \quad (7)$$

(Evans, Futoma, and Lombana 1978). The efficiency function EFF(NACT) for the current activity NACT depends on Z. Thus the increment DELTIM of effective work time projected over the next time-step of width DTNOW is

$$\text{DELTIM} = \text{DTNOW*EFF(NACT)*IUP}, \quad (8)$$

where IUP is the product of seven binary variables respectively indicating whether there are sufficient levels of each of the six supplies on the drilling vessel and whether the marine riser is connected. The effective work time SS(2) projected to the end of the time-step is based on the effective work time SSL(2) at the beginning of the step:

$$\text{SS(2)} = \text{SSL(2) + DELTIM}. \quad (9)$$

When SS(2) rises to the nominal effective work time SS(3) for the current activity, the state-event defining the end of the current activity is automatically invoked by the SLAM executive routine.

Difference equations are also used to model the unloading of supplies from the supply ship. For example, the change DELFS in the fuel level on the supply ship is projected over the next time-step as follows:

$$\text{DELFS} = \text{DTNOW*UNLD(1)*IUF}, \quad (10)$$

where UNLD(1) is the fuel unloading rate, and IUF is the product of four binary variables respectively indicating whether each of the following conditions is true: (a) a supply ship is actually on site with supplies to unload; (b) the wave height is low enough to unload the supplies; (c) the drilling vessel constraint on the total supply weight is not currently binding; and (d) fuel is the supply that should be unloaded now. Thus the supply ship fuel levels SSL(15) and SS(15) respectively defined at the beginning and end of the time-step are related by the equation

$$\text{SS(15)} = \text{SSL(15) - DELFS}. \quad (11)$$

When SS(15) falls to zero, the associated state-event selects the next supply to be unloaded.

Supply levels on the drilling vessel are regulated by more complex difference equations. For example, the drilling vessel fuel levels SSL(4) and SS(4) respectively defined at the beginning and end of the time-step are related by the equation

$$\text{SS(4)} = \text{SSL(4) + DELFS - DELTIM*RATE1}. \quad (12)$$

The usage-rate components for fuel, water, and gel (RATE1, RATE2, and RATE4 respectively) are sampled from triangular distributions at the same time intervals used for the weather models. All other supplies are uniformly allocated over prespecified activities. As depicted in Figure 2, there are four state-events associated with the drilling vessel fuel level:

1. When SS(4) rises to the nominal capacity CAP, another supply is selected for unloading.
2. When SS(4) falls to the nearly critical level ORL, the unloading of fuel is resumed if possible.
3. When SS(4) falls to the critical level MIN, drilling vessel operations go down. If possible, unloading of a new supply ship is initiated.
4. When SS(4) rises to the operations restart limit, drilling vessel operations are resumed.

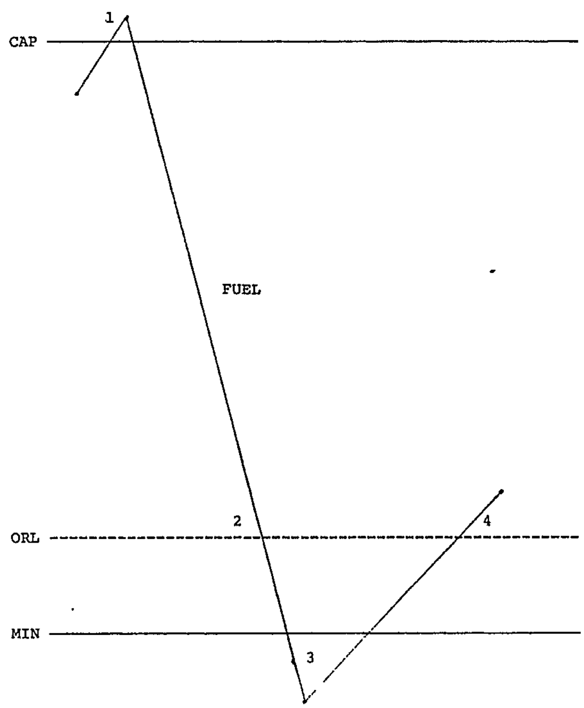

Figure 2: State-Events Associated with Fuel Level on the Drilling Vessel

A similar control scheme applies to the other supplies on the drilling vessel.

The total supply weight on the drilling vessel is projected to the end of the time-step by summing over all relevant supply levels:

$$SS(21) = \sum_{J=4}^{9} SS(J). \tag{13}$$

When SS(21) rises to the total weight limit, unloading of the supply ship is halted by setting the total-weight-constraint indicator to zero. When SS(21) falls below the unloading restart limit, this indicator variable is reset to one.

A difference equation is also used to govern the position of a supply ship in transit between the port and the site. The travel speed depends dynamically on the wave height. A state-event defines final arrival at the destination and the initiation of supply ship loading or unloading.

3.2 Process-Interaction Model

The overall operation of the drilling vessel is represented by the SLAM subnetwork shown in Figure 3. As previously discussed in connection with equation (9), the state-event defining the end of the current activity occurs when effective work time SS(2) rises to the nominal effective work time SS(3). This causes the DETECT node labeled ANCH to be released. If the activity number XX(1) is less than 18 (the last activity number for the well design under discussion), drilling is advanced to the next activity. At the end of the last activity, the EVENT node labeled EV7 is realized. This causes a discrete-event routine to check for well completion (namely, the restoration of adequate levels of each supply on the drilling vessel). The termination condition is rechecked every one time unit (6 hours) until the run can be stopped.

The flow of supply-ship traffic between the port and the rig is represented by the SLAM network shown in Figure 4. Each entity flowing through this segment of the model represents a supply ship. The supply-ship fleet size XX(50) is specified by the user. At the ASSIGN node labeled SUP1, each entity is assigned seven attributes respectively denoting the supply ship number and the weight of each supply carried. After the drilling vessel is moored (that is, after the DETECT node ANCH has been released at the end of the first activity), each supply ship arrives on-site. The realization of the ALTER node labeled SITE allows any empty supply ships on the site (that is, entities queued at the AWAIT node APSS) to return to port. An arriving supply ship then queues up at the AWAIT node AWUN to unload supplies onto the rig. Only one supply ship is allowed to unload at a time. Symbolically, the supply ship to be unloaded goes to the EVENT node labeled SUP; this invokes the discrete event routine containing the supply-ship unloading logic. The overall supply-unloading activity is completed when the SLAM routine STOPA is called by the associated state-event routine with an entity code of 1. When the empty supply ship flows into the FREE node FRUN, the next loaded supply ship queued at the AWAIT node AWUN is sent to the EVENT node SUP. When the empty supply-ship entity flows in the ALTER node labeled RPSS, the capacity of the "port-pass" resource SSHIP is reduced by one. This ensures that the empty supply ship will remain on-site (that is, at the AWAIT node APSS) until it can be replaced by a loaded supply ship. When a port-pass is issued to the empty supply ship, the pass is immediately relinquished at the FREE node FPSS; and the return trip to port is initiated at the ASSIGN node LVST. The empty supply ship reaches port when the SLAM routine STOPA is called by the associated state-event routine with the entity code II assigned to the supply ship at the node LVST. Upon arrival at the EVENT node labeled PORT, a discrete-event routine executes the supply-ship loading logic. Loading of the supply ship is completed in DD(2) time units, allowing the supply ship to return to the site. The loaded supply ship arrives back at the rig when the SLAM routine STOPA is called by the associated state-event routine with the assigned entity code II. This cycle of supply-ship activities continues throughout the simulation.

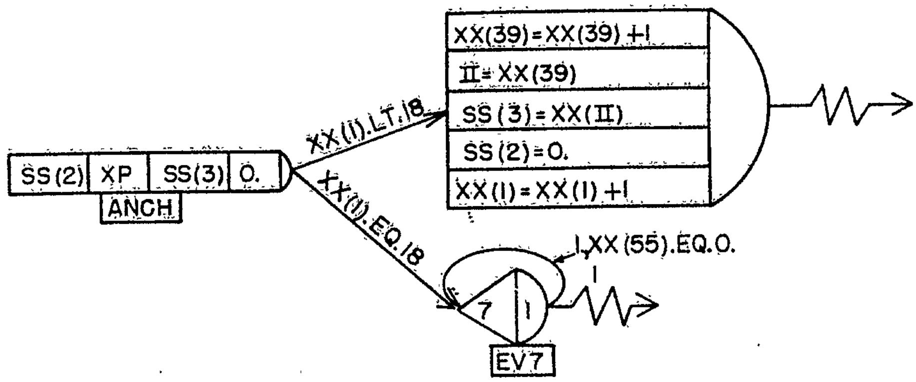

Figure 3: SLAM Subnetwork Model of Overall Drilling-Vessel Operations

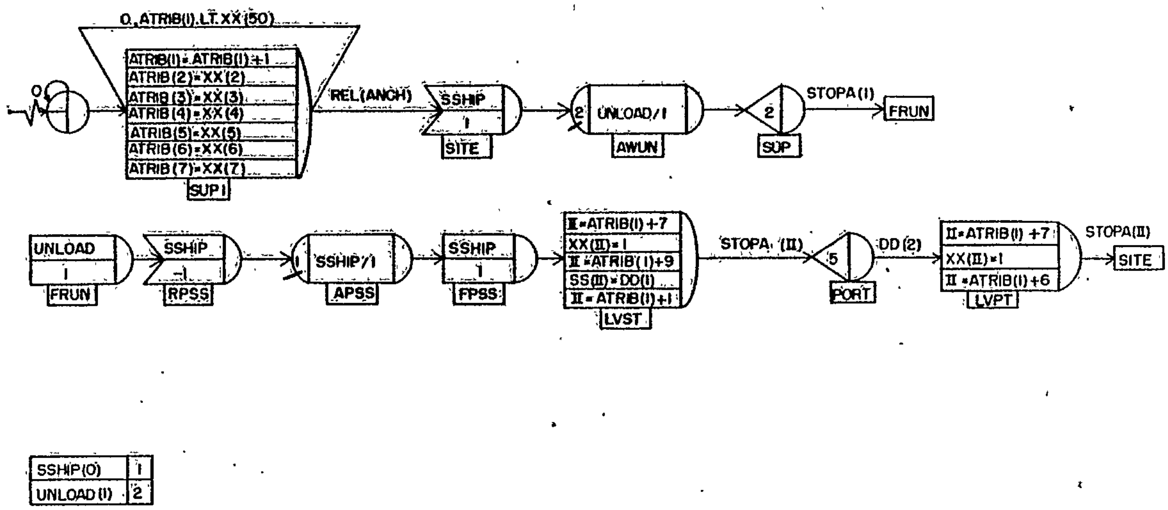

Figure 4: SLAM Subnetwork Model of Supply-Ship Traffic Flow

3.3 Discrete-Event Submodel

Apart from representing the storm arrival process, the discrete-event submodel consists entirely of previously discussed support routines for the other submodels. When a storm-arrival event occurs, the storm class is randomly sampled from an empirical distribution for the corresponding month. The appropriate intervention terms are then set to one in equations (2) and (4). The storm duration is also sampled from an empirical distribution for the corresponding month, and an end-of-storm event is scheduled. When the end-of-storm event occurs, the intervention terms in (2) and (4) are reset to zero, and the next storm-arrival event is scheduled.

4. DATA ACQUISITION

In addition to the hindcast data described in §2.2, ARCO also provided values for all of the input parameters characterizing the fleet of supply ships as well as four alternative drilling vessels. The company specified an exploratory well design with eighteen activities whose operation times were assumed to be triangularly distributed. These distributions were used in the study because there was not enough historical data available to warrant fitting a more complex distribution. The response amplitude operator (RAO) for each drilling vessel was provided to ARCO by contractors. Operation restart limits depicted in Figure 2 were selected by ARCO.

5. MODEL VERIFICATION AND VALIDATION

To verify the proper execution of the simulation model, we used standard software development techniques. We used structured walk-throughs to review both the overall design of each submodel and the detailed implementation of the support routines (Myers 1976). Top-down debugging allowed us to identify and correct inadequacies in the process-interaction and continuous submodels at an early stage; thus we were able to avoid excessive "patching" of the model's code (Ledgard 1975). The computer program was developed using the Minnesota FORTRAN (MNF) compiler (Frisch and Liddiard 1976) on the CDC Dual Cyber 170/750 at The University of Texas. We used the MNF trace options extensively in the initial stages of debugging the model. However, our chief debugging tools were the standard SLAM support routines for tracing model operation and for generating plots and tables of important system status variables. To isolate and correct infinite loops in the continuous submodel, we embedded a special trace facility at key interface points in the combined discrete-continuous time-advance logic of the SLAM executive routine.

Validating the accuracy of the model's performance predictions was less clear-cut (Law and Kelton 1982). Essentially, validation consisted of continual interaction with knowledgeable ARCO personnel. Their evaluation of the model's outputs formed the basis for all revisions and extensions.

6. CONCLUSIONS

The simulation model developed in this study is considerably more flexible than previous models of offshore drilling operations. The application of Box-Jenkins time series methodology to sea state modeling has proved to be a substantial improvement over the previous approach. Further work to develop a multivariate time series model with a more refined storm model is currently being completed. Eventually the model will also be expanded to include response characteristics of the drilling vessel.

The most innovative aspect of the simulation model is the use of difference equations to represent the dynamic dependence of the efficiency of offshore drilling operations on the prevailing weather conditions. The integrated model is easily understood by the users and is capable of being modified to include other aspects of an offshore drilling project. Atlantic Richfield Oil and Gas Company has installed the model and is currently using it to select the drilling vessels for future projects, to evaluate alternative well designs, and to predict the effect of mid-project changes in the conditions at a drilling site.

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